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AERONAUTIC INSTRUMENTS.

By E. Everling and H. Koppe.

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TECHNICAL MEMORANDUM NO. 249.

AERONAUTIC INSTRUMENTS.*

By E. Everling and H. Koppe.

Summary.

The development of aeronautic instruments. Vibrations, rapid changes of the conditions of flight and of atmospheric conditions, influence of the air stream all call for particular design and construction of the individual instruments. This is shown by certain examples of individual instruments and of various classes of instruments for measuring pressure, change of altitude, temperature, velocity, inclination and turning or combinations of these.

Instrument Development.

The fundamentals of instruments for aircraft fall into many classes. Instruments for navigation resemble those for ocean navigation; some instruments are developments of the indicators of atmospheric conditions used in meteorology and free balloon flight; velocity indicators are derived from the technic of ventilation; inclinometers from surveying; tachometers and indicators of applied pressures from engine technics. With the realization of the performance required from the instruments in flight all

* Translation by W. G. Brombacher, Bureau of Standards, from Zeitschrift des Vereines deutscher Ingenieure, April 1, 1922, Vol. 66, No. 13, pp. 322-326.

these types with their fine mechanical workmanship have been modified to take account of the various factors encountered in flight: the constant vibration caused by the engine, by the change in the direction of the air stream or by gusts, and the irregular severe shocks caused in landing, all of which require balancing and damping of the multiplying and indicating or recording members; the acceleration of gravity superimposes itself on the variable inertial forces so that gravity cannot be measured separately; the strong air stream which distorts the pressure distribution in the neighborhood of aircraft and thereby affects the measurement of airspeed; air pressure, altitude, temperature and humidity vary rapidly and must be indicated without lag; they change at times over a small range, which can be indicated only by an open scale; the weights and sizes of the instruments must be small.

How these requirements are met will be shown by some examples of the instruments used to determine position, flight performance and atmospheric conditions.

Barograph.

For usual determinations of the altitude of flight one requires solely the air pressure, although the altitude does not vary solely with the pressure, but is also dependent on the temperature; furthermore, instrument performance is directly influenced by temperature. Owing to the vibrations and shocks experi-

enced and to the cramped space on the aircraft only aneroid barometers can be used, the use of mercurial barometers being impossible. The instruments contain corrugated boxes or diaphragms nearly evacuated, which oppose the pressure of external air with the help of internal springs - thus being protected against corrosion - or with external springs attached to the boxes. The deflection of the diaphragms and springs due to a decrease of the atmospheric pressure is carried over to an indicator or recording pen by levers or chains.

The indicating mechanism, more so, the elasticity of the diaphragms and above all that of the springs are affected by change in temperature. In order to reduce these effects at any particular altitude, the diaphragms should contain a small residue of air or gas, which expands with rising temperature and so opposes the decreasing stiffness of the springs.

The greatest defect of spring metal when the forces are changed quickly, is the after-effect, which is most important in altimeters as they indicate too high an altitude when the descent is rapid and thus may prove fatal to the pilot. The firm of Carl Bamberg decreased the after-effect by strengthening the middle part of the diaphragm, as a result of research* and by using springs whose loads were under the elastic limit as far as possible. A mechanical type of compensation for after-effect was built by the firm C. P. Goerz using a scheme suggested by

* Warburg and Heuse, "Über Aneroide. Zt. für Instrumentenkunde. Feb. 1919, p. 41.

K. Bennewitz, which is a masterpiece of compensation.* At the ends of a lever (a) (Fig. 1), operate two pressure elements (b) and (c) one against the other. The group (b) has for a given pressure difference a distinctly greater extension than group (c), but by selection of suitable metals and by adjustment both are made to have about the same after-effect. If the lever arm (a) be divided in the ratio of the after-effects of the springs, then lever (a) will not communicate any motion to the pen arm due to the after-effect, but on the other hand the point of connection to lever (d) will rise and fall because of the different effect of atmospheric pressure upon elements (b) and (c).

Through the four levers (d) this motion will be communicated by the turning arm (h) to the pen arm (e) which, as usual, traces on a recording drum (f) with a clockwork drive. For adjusting the zero the diaphragm (c) is raised and lowered by screw (g).

An equally spaced altitude scale is desirable in instruments used in the testing of aircraft as well as for the direct indication of altitude and rate of climb. The scale divisions of altigraph charts for the range of the pen may be greatly shortened at high altitudes partly owing to the non-uniform performance of the multiplying mechanism and pressure elements but, mainly owing to the law connecting altitude and air pressure, the logarithm of the latter varying as the altitude. An equally spaced altitude scale is achieved in the Goerz altigraph (Fig. 2),

* This method of compensation is effective only for one speed of ascent and descent.- Translator.

by a divided pressure lever (cc) extending from the pressure element (a) to the next lever (b) of the multiplying mechanism. This joint is guided by lever (d), which rotates about the shaft (h) of the pen arm. This lever with its complicated motion is so chosen that an equally divided altitude scale is obtained. By raising or lowering the group of diaphragms by turning a screw (g), the pen arm (e) is adjusted for zero upon the drum (f).

As an example of compensation for disturbing accelerations the altimeter built by Goerz (Figs. 3 and 4), may be noted. Every lever is made symmetrical in relation to its axis; even the diaphragms are attached on opposite sides and the pointer is duplicated inside the case so that the two pointers make a symmetrical system. The zero adjustment is accomplished by turning the plate upon which is mounted the entire mechanism. This design accomplishes complete balance for linear accelerations and so nearly gives compensation for angular accelerations, assuming homogeneous material, that the vibration due to this cause is less than that which would be produced by a very small projecting mass on a shaft. Furthermore, vibrations cause no injury to the mechanism; in fact the effect is about that found upon tapping an ordinary aneroid barometer. Fig. 4 shows knob at top for adjusting zero point.

Statoscope.

It is not desirable to use altimeters for certain requirements of aircraft performance and for certain demands of special

types of aircraft as their accuracy is not sufficient to indicate small deviations in the altitude of flight. These deviations are very important in measuring airspeed in which every altitude change means gain or loss of energy. One is aided by special apparatus in indicating deviations from a given altitude such as has been long known to free balloon pilots and which has been adapted by a stroke of genius to the measurement of rate of climb.* Only toward the end of the war was there any attempt made to adapt this instrument to the performance requirements of aircraft. Furthermore, in the announcement of the conditions of competition for the Rumpler prize the need for a statoscope was also emphasized. The Bamberg statoscope (Figs. 5 to 7), contains a multiple diaphragm (a) having a downward deflection limited by the free member (b) which rests on the fixed member (c) when the lower limit of a given altitude change has been exceeded. A spring (d) balances the outside pressure; its tension can be adjusted by screw (e) which turns the graduated dial (f) until the reading of the desired altitude of flight on the dial coincides with the marker (g). A lever (h) presses against lever (k) near its shaft (i) with a pressure proportional to the diaphragm deflection. Lever (k) finally carries over the motion to the pointer (l) and there indicates the deviations from the chosen altitude. Exceeding the set altitude during flight causes the pressure link (h) to leave the shaft (i). Further, this instrument allows the ad-

* A. Bestelmeyer, Ballonvariometer. Deutsche Luftfahrer-Zeitschrift. Vol. 16, No. 25, Dec. 11, 1912, p.615.

justment of the mechanism to the desired altitude of flight to be made while on the ground.*

The density statoscope built by Goerz* uses a U-tube manometer with a valve opening to the atmosphere. This instrument indicates pressure changes by the rise and fall of the fluid from the moment the valve closes. The cut-off valve connects with an air reservoir which is in the form of a coil and is swept by the air stream. This makes it possible, conforming to the letter of the prize conditions, to keep constant the air density instead of the altitude, relative to the air pressure.**

Temperature.

While data on flying speed show its dependence on altitude or air pressure, knowledge of the air density is required in addition to the air pressure for the comparison of climbing ability and exclusively for the comparison of ceilings. In order to compute it, the temperatures corresponding to the air pressures must be known. These may be read on mercury or spirit thermometers which are thoroughly ventilated and well protected from exhaust gases and heat rays, or recorded, using liquid-filled bourdon tubes, or bimetal spirals. The latter alters its curvature with

*Further details: H. Koppe, Über den Rumpler-Preis-Wettbewerb, Zeitschrift für Flugtechnik und Motorluftschiffahrt. Vol. 13, No. 2, 1922, pp. 33-40.

** Strictly speaking a pressure statoscope indicates more exactly constant altitude than a density statoscope indicates constant density. On this and other instruments, see E. Everling, Flugleistungsprüfung, Abschnitt E, Handbuch der Flugzeugkunde, Vol. 1, Berlin, 1922.

temperature because of the difference of the thermal expansion coefficients of its component parts and thus actuates a pen arm. The temperature instrument must be well ventilated, in order to cut down lag, and sturdily constructed and protected by damping against vibration. To this end the AEG triple recorder,* which records airspeed, pressure, and temperature, has air damping by means of graphite rods.

Of other temperature recorders that of the R. Bosch Co., which was widely used during the war may be mentioned, and also the carefully built bimetal spiral in the Wigand Meteorograph** research in aircraft from the Drachen meteorograph and records air pressure and temperature, also humidity; in determining the air density it is only necessary to consider the average humidity. Wigand's instrument shows itself ahead of many in its streamlined case, its carefully designed spring suspension and by the clear and sharp, dependable, although less convenient record on blackened paper, thus eliminating ink.

Airspeed.

The measurement of airspeed with Robinson's or a propeller anemometer, with pitot and venturi tubes, is now being well done. The pressure element is similar to that of the aneroid barometer as is also the multiplying mechanism although more delicate than

* G. König, Energiemessungen durch Steig- und Gleitflüge. ZFM, Vol. 11, No. 12, June 30, 1920, pp. 170-173.

** A. Wigand, Aero-logische und Luftelektrische Flüge und ihre Bedeutung für die Luftfahrt. Berichte und Abhandlung der Wissenschaftlichen Gesellschaft für Luftfahrt (Beihefte zur ZFM, Vol. 1, No. 4, April, 1921, pp. 43-60).

in the aneroid barometer. The fundamental difficulty of every measurement of airspeed in aircraft, that of placing the airspeed nozzle in undisturbed air, can be overcome only in certain cases.

In spite of the difficulties the instruments described below were developed with gratifying results. One, which is combined with other instruments on a recording drum has been mentioned. The airspeed recorder of Wieselsberger* of the Göttingen Aerodynamic Research Laboratory also demands attention (Figs. 8 to 10), because of the careful design, arrangement of the moving parts, and the guarding against the effects of linear as well as angular accelerations and also against centrifugal couples. The case is airtight and keeps the measuring element under the static pressure of the atmosphere. For this purpose it is connected by a tube to the side openings of a Prandtl (Pitot) pressure tube. The pressure change acts against spring (b), its deflection is transmitted by the levers (cc), which has adjustable counterpoises, to the light aluminum pen arm (d), which records on a blackened drum (l). If the contact force upon the blackened drum is smaller than that required with ink, the pressure of the recording point can be decreased by an adjustment. The axes of rotation are knife edges (f), (g), which are held against their bearing plates by helical springs, and the levers are connected by adjustable plate springs. The links (hh) are also plate springs.

* C. Wieselsberger. Ein Manometer zur aufzeichnung von Fluggeschwindigkeiten. ZFM, Vol. 12, No. 1, Jan. 15, 1921, pp. 4-6.

Of the hose connections (i), the one that connects with the pitot tube has a throttle, so that rapid fluctuations of pressure may be smoothed out.

In the Goerz venturi airspeed recorder, (Figs. 11 and 13), the venturi tube (a) projects in front of the aircraft from its support (b) where the air stream is least disturbed. The suction at the throat section of the venturi (a) is connected to the diaphragm element (c) by the hollow support and the tubing (bb) and is, as usual, recorded on the drum (f), by means of the rod (d), by the pen arm (e). The case is covered by heat insulation (g), and is under the pressure of the surrounding air which does not, at the most, vary much from static pressure at the nozzle when compared with the large suction of the venturi.

In general it may be said that instruments which rely for a counter force upon springs or weights, as pitot and venturi airspeed indicators, are dependent upon air density, while on the other hand the speed of frictionless running anemometers and propellers without vortex damping etc., depends only on the velocity.

Inclination.

The fore and aft inclination and the lateral inclination with reference to the perpendicular are important for judging the position of flight. The various pendulums, liquid levels, and the like are not damped sufficiently against disturbing vibrations until they indicate with too much lag. The Goerz inclinom-

eter (Figs. 13 and 14), avoids this by enclosing a thin section of a dark colored liquid between two parallel plates of glass with a ring-shaped support. A level scratch indicates the correct position. For fore and aft inclination (Fig. 13) there are divisions up to 40° , for lateral inclination (Fig. 14) there are position marks for 15° inclination to right or left.*

An inclinometer made by Fuess is worthy of description, differing from the level with the usual air bubble by using a steel ball in the curved tube, which is filled with a viscous fluid, in other words, a pendulum with excellent guidance and damping.

All inclinometers have the property of not indicating the true vertical, but rather the direction of the resultant of gravity and forces due to motion of the aircraft. For example, in banking they indicate the resultant of gravity and centrifugal force. Since these act simultaneously on the aircraft, it is not possible by any arrangement to eliminate gravity in order to indicate the vertical.** The lateral inclinometer therefore indicates zero inclination in turning if the airplane is banking properly. It does not, therefore, differentiate between correct turning and straight horizontal flight.

Turning.

As long as the earth or the horizon is visible, a knowledge

* H. Boykow, Die instrumentelle Unterstützung des Fliegens. Zt. für technische Physik, Vol. 2, No. 9, Sept., 1921, pp. 238-244.

** E. Everling, Die wahre Neigung von Flugzeugen. Der Motorwagen, Vol. 22, No. 28, Oct. 10, 1919, pp. 531-533. Also Neigungs- und Kurvenmessung bei Flugzeugen; Der Motorwagen, Vol. 24, No. 24, Aug. 31, 1921, pp. 491-493.

of the position of the aircraft with reference to the apparent vertical is sufficient. In clouds or mist and at night the pilot must know either the true inclination or the rate of turning. The gyroscope, used somewhat as an artificial horizon in aiming an airplane's guns, can indicate the true vertical for a time, but is sensitive to disturbances, in particular to ordinary variations of the course of the ship.*

Let a free gyroscope be supported in gimbals and let it be deprived of a certain degree of freedom by guiding its frame in spindles. Let the frame be fastened to the aircraft by springs, in such a way that the spring deflection measures the moment acting on the gyroscope. The moment, deflecting the springs will be caused by the turning of the aircraft about its normal axis, providing the axis of the gyroscope is perpendicular to the normal axis of the aircraft and especially if the gyro axis is parallel to either the lateral or longitudinal axis of the aircraft. The Drexler turn indicator** is built on these principles (Figs. 15 to 17). The gyro (a), an alternating current synchronous motor making 20,000 revolutions per minute, is mounted on ball-bearings in the frame (b). When the aircraft turns, the frame and motor turn about the horizontal spindles (cc). Spring control is afford-

* K. Bennewitz. Über flugtechnische Instrumente Tech. Berichte der Flugzeugmeisterei, Vol. 3, No. 5, 1918, pp. 160-165; there may also be found a discussion on inclinometers, the fundamental theory of the Drexel turn indicator, pitot tube pressure instruments, pitot tube turn indicators. Also H. Boykow Bemerkungen zum Artikel: "Zur Störungstheorie des Kreiselpendels" ZFM, Vol. 10, Nos. 11/12, June 28, 1919, pp. 124-125.

** Wertheim, Der Drexler-Steuerzeiger. Flugsport, Vol. 12, March 3, 1920, pp. 104-114.

cases shown in Figures 18 to 20. The inclinometer ball remains at the zero position for a theoretically correct bank (Fig. 18); for overbank, sideslip inward, the ball moves to the left shown in Figure 19; for underbank, sideslip outward, the ball moves to the right, as shown in Figure 20, the radius of curvature of flight remaining unaltered for the three cases. The positions of the plane for these three cases are shown in Figures 21 to 23.

For the case where no adjustment of the inclinometer is necessary, the position of the inclinometer, inclinometer ball, and hand are shown for a left hand turn with correct bank in Figures 24 and 27. If, in the judgment of the pilot, the plane requires overbanking during a turn and the inclinometer is accordingly adjusted, the positions of the elements during a turn so overbanked are shown in Figures 25 and 28; for a plane requiring underbanking the positions are shown in Figures 26 and 29.

Figs. 24-26.- Drexler turn indicator: a, inclinometer with steel ball; b, "shield" (supporting level); c, slide for raising and lowering shield; d, guide; e, screw for adjusting slide c; a₁, pivot of pointer; b₁, supporting pin of shield b, adjustable vertically; c₁, pivot of shield b on slide c.

These are the adaptations to the requirements for aeronautic instruments including the exacting conditions during turns.

Translator's Note: Certain sections of the paper have been translated rather freely, especially the section on the Drexal turn indicator.

Translated by
W. G. Brombacher,
Bureau of Standards.

ed by means of the series of corrugated metal diaphragms (ee) which are connected by small holes and are filled with a liquid for the purpose of producing the necessary damping. The bent bar (f) carries this motion to the pointer (g) whose position is shown on the milk-glass dial (h) by a lamp (i); the transformer (k) adjusts the current for the lamp. (l) is an inclinometer (a steel ball in a curved glass tube filled with a liquid), (m), an adjustable device which causes tilting of the inclinometer when the gyro precesses, and (n), a screw which regulates the amount of tilting for a given precession. The inclinometer, when adjusted so as to be unaffected by the precession of the gyro, serves to indicate the departure of the normal axis of the plane from the theoretically correct position, which is that parallel to the resultant of centrifugal and gravitational accelerations. The inclinometer, in any other adjustment, is tilted by the precession of the gyro and now indicates a departure, not from the theoretically correct position, but from a position which varies from the theoretically correct position by the amount of the tilting. The necessity for this adjustment varies with each plane and pilot and the amount is determined by the pilot for his plane in accordance with his experience in test flights in good weather.

The operation of the Drexler turn indicator is illustrated in Figures 18 to 29 for several cases. Consider the inclinometer so adjusted that it is not affected by the gyro precession. The gyro hand indicates to the left for a left hand turn in all the